# A Compact, Efficient, Optically Pumped Deep UV Laser *


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***Abstract*—We are developing a compact and efficient deep UV laser under the DARPA LUSTER program. A key innovation of the laser is its novel double intra-cavity configuration with a coupled resonant fourth harmonic cavity that avoids the use of an independent external resonant cavity. In our Phase 1 project over 190 mW power at 234 nm wavelength was demonstrated by harmonic conversion (with a BBO crystal) of the intra-cavity doubled 468 nm output of an optically pumped 936 nm wavelength InGaAs VECSEL. In Phase 2 a highly compact early prototype 232 nm deep UV laser has been demonstrated using a higher efficiency second generation 928 nm VECSEL.**



***Keywords—Deep UV laser; near-IR VECSEL; Nonlinear frequency conversion; Optical pumping; Tactical Raman Sensor.***


## I. INTRODUCTION

Continuous wave deep ultraviolet (DUV) lasers in the 220-240 nm wavelength range are required for numerous applications, such as tactical chemical and biological sensors, Raman spectroscopy for detection of explosives, narcotics and chemicals, interferometric lithography, defect inspection on semiconductor wafers, etc. DUV excitation is especially beneficial for Raman spectroscopy sensors, because, Raman emission occurs in a fluorescence-free region of the spectrum at wavelengths $\lambda < 250$nm, whereas fluorescence occurs at $\lambda >$ 250nm, thereby eliminating obscuration of the weak Raman signals by fluorescence. Furthermore a strong resonance Raman enhancement of the Raman cross section (CS), occurs for excitation at $\lambda < 250$ nm, causing large increases in the CS over and above the normal $(1/\lambda)^4$ increase of Raman CS with $\lambda$. The main objective of the DARPA LUSTER BAA program was to develop ultra-compact, high efficiency DUV lasers with 1 W output. In this paper we present the highlights of a compact laser [1] that we are developing under the DARPA LUSTER BAA program. It is based on a near-IR optically pumped vertical external cavity surface emitting laser (VECSEL) and two nonlinear frequency conversion steps to obtain the DUV output. Our approach is similar to the UV laser [2] demonstrated earlier by researchers at the University of Arizona, wherein 215 mW CW output at 244 nm wavelength was obtained by nonlinear frequency conversion of a near IR 976 nm optically pumped VECSEL.

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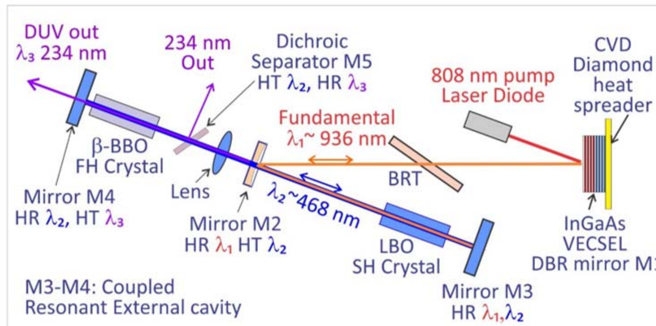


Fig 1. Optical layout of the compact deepUV laser with a coupled resonant fourth harmonic cavity.

## II. DOUBLE INTRA-CAVITY LASER DEVELOPMENT

Fig. 1 shows the optical layout of our double intra-cavity DUV laser that uses a novel coupled resonant cavity for generating the fourth harmonic output instead of requiring an independent external cavity. This configuration makes the laser highly compact and more importantly reduces the internal losses by reducing the number of optical components in the beam.

A multiple quantum well InGaAs/GaAs/GaAsP VECSEL chip with a distributed Bragg reflector and bottom emitting structure operating at ~936 nm with a tuning range of > 10 nm was designed and grown. It was attached to a chemical vapor deposited diamond heat spreader with Indium solder, and placed on a heat sink. The bottom emitting structure with its shorter path to heat sink is well suited for high power operation. The fundamental and second harmonic 468 nm blue are generated in a V folded cavity (see Fig. 1), formed by the VECSEL chip’s flat DBR mirror M1, a folding concave mirror M2, and a flat mirror M3. The VECSEL chip is AR coated to reduce Fresnel losses and is optically pumped by focusing the output of a 15 W, 808 nm fiber coupled laser diode on the chip surface. High efficiency was achieved by matching the pump spot size to the size of the $TEM_{00}$ mode of the resonator V-cavity and by using an appropriate laser cavity length and curvature for the folding mirror M2. Over 3 W output in blue for 12 W of pump power, over 25% efficiency of conversion from 808 nm pumping wavelength to 468 nm blue, and good beam quality ($M^2 < 1.4$) were obtained.

The coupled external cavity formed by mirrors (M3, M4) is resonant at the blue wavelength and provides large enhancement of the blue beam. DUV output is generated in a bulk β-BBO nonlinear crystal in both the forward and backward directions. A UV beam exits from the resonant cavity via a HR/HT M4 mirror. A Brewster angled dichroic beam separator (coated for R > 98% of the s-polarized UV, and R < 1% no-loss transmission of the p-polarized blue light) is placed in the coupled cavity to reflect the back converted UV beam.

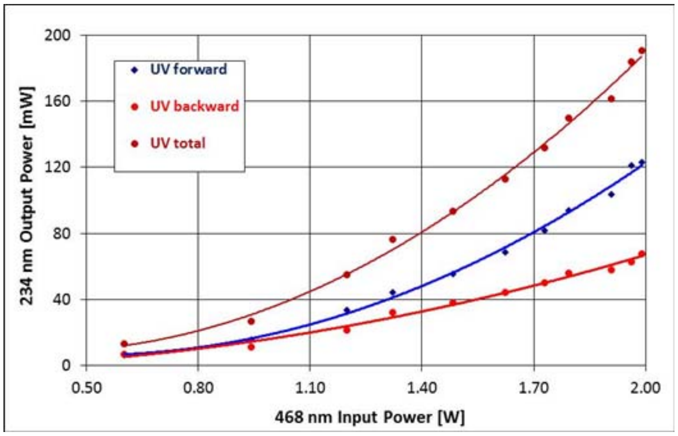


Fig 2. UV power versus blue power obtained in the forward output beam and from the separator mirror M5 in the resonant coupled cavity shown in Fig.1.

Fig. 2 shows the forward UV output through the mirror M4 without the separator M5. About 120 mW at 234nm was obtained for a blue beam power level corresponding to 2 W. The UV output generated in the backward direction and reflected out of the resonant cavity by inserting the dichroic separator mirror M5 is also shown in Fig 2. A compact prototype DUV laser, was built and demonstrated in Phase 1 of the project.

## III. Development of A More Compact Laser

The main goals of the Phase 2 of our project were to further reduce the size of the laser (see Fig 3), and increase the overall efficiency and UV output power of the laser. A second generation VECSEL gain structure was designed to provide a 5 to 10% improvement in the efficiency of the fundamental laser.

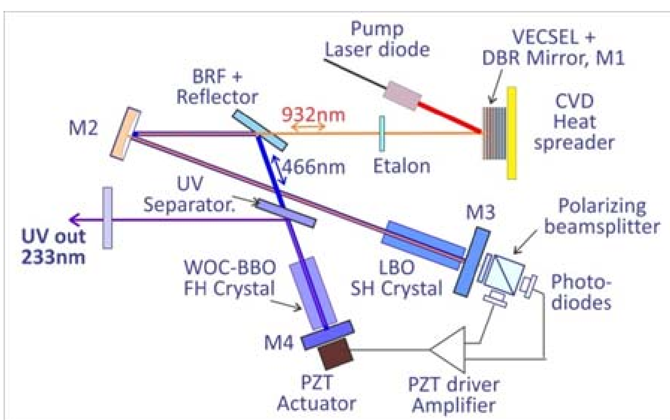


Fig 3. Schematic of the highly compact configuration of the deepUV laser. Also shown is the PZT actuator for frequency locking feedback the coupled resonant fourth harmonic cavity.

This was done by increasing the number of quantum wells that results in better pump absorption and higher gain, and by slightly increasing the detuning between the room temperature photoluminiscence and the sub-cavity resonance to provide a higher slope efficiency with only a marginal increase in the lasing threshold. A new wafer growth was completed and the resulting VECSEL chips have indeed provided > 7% improvement in efficiency in the blue conversion to nearly 27%. By adding a high reflectivity coating to the Brewster angled birefringent filter as shown in Fig 3, we have reduced the size of the laser. Shown in Fig 4 is an early prototype highly compact DUV laser (which is already one third the volume of the phase I laser) that was built and demonstrated at the recent D-60 event - DARPA's 60$^{th}$ Anniversary symposium and exhibition.

Both the UV output power and conversion efficiency will be increased by using a piezo-electric transducer to control the

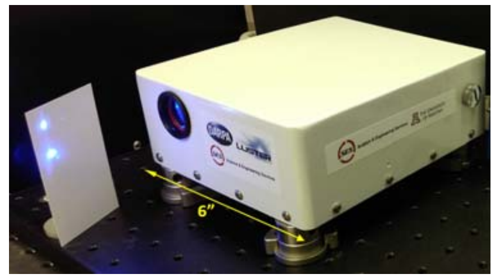


Fig 4. An early Phase 2 prototype compact DUV laser was demonstrated at the DARPA D-60 event. Seen on left are the 232nm (top) and 464nm beams.

cavity length to make it resonant for blue beam wavelength, and by using a novel segmented walk-off compensated BBO crystal that will reduce the walk off during fourth harmonic conversion. Work is in progress to implement these two steps and the resulting improvements will be reported.

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"The views, opinions and/or findings expressed are those of the author and should not be interpreted as representing the official views or policies of the Department of Defense or the U.S. Government."

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